Spiral passive electromagnetic sensor (SPES) for smart sensing and de-icing.

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ABSTRACT

The objective of this work was to develop a wireless Spiral Passive Electromagnetic Sensor (SPES) to monitor the complex permittivity of a surrounding medium. The sensor is a self-resonating planar pattern of electrically conductive material. Investigation were conducted to demonstrate the capability of the SPES to monitor humidity and temperature gradients, and acting as an ice protection tool. An oscillating signal is used to interrogate remotely the sensor with a single loop antenna or wiring it directly to a spectrum analyser and monitoring the backscattering signal. The excited sensor responds with its own resonant frequency, amplitude and bandwidth that can be correlated to physical quantities to be monitored. Our studies showed the capability of the sensor to monitor temperature and humidity changes in composite materials and uniformly produce induction heating when the conductive path is activated by an external electric power supply that can be used for deicing of aircraft structures.

Keywords: damage detection, smart sensor, de-ice, temperature sensor, humidity sensor, resonant frequency shifting.

1. INTRODUCTION

For many years engineers have been searching for ways to obtain information on how structure is behaving in service by incorporating, at the time of construction or subsequently, sensing devices which can provide information about their health such as strain, temperature, humidity, and the presence of defects (e.g. crack, delamination, porosity, etc.). In the recent years structures and infrastructures tend to contain more integrated sensors in order to collect data on its health and/or on different environmental parameters [1, 2]. Moisture is one of the largest concerns for building since it is the single most important agent of building deterioration [3]. Moreover the control of relative humidity and temperature is essential for improving the aircraft cabin air quality [4]. Whereas nowadays temperature measurements can be performed with a satisfactory accuracy, measurement of humidity results much more complex [5, 6]. The highest percentage of the current humidity sensors are based on the capacitive technique, have the feature of ease fabrication, low power requirement and linear response [7, 8]. Nowadays, with the steady increase of the use of composite materials in the aerospace industry, a significant amount of work has been conducted for the development of non-destructive inspection as well as for structural health monitoring system [9, 10]. Furthermore, for an effective monitoring of flaws within the structure a large number of sensors distributed over a large area are required. The presence of multiple sensors on the same structure require the use of complex algorithm for the analysis of the data [11, 12]. Most of the sensors actually used for monitoring humidity, temperature or for SHM system are single-functional elements. This require the use of a sensor network were different device are integrated. The health of structures could be strongly affected also by the presence of ice. Icing of overhead power line or structure is a serious problem throughout the world [13-15]. In particular, for aviation in-flight ice formation on airplanes is one of the most critical and current problems. Indeed an in-flight anti-/de-icing technologies that can operate on metal structures as well with composite structures is required [16, 17]. Moreover for wired sensor, the presence of multiples sensors results in complexity and weight penalties associated with the installation of the sensors network [18, 19]. Another challenging task is to utilise sensor systems to monitor parameters in sealed environment, within construction elements, inside food and pharmaceutical packages. For these reasons there is a growing need to design and manufacture passive wireless sensors [20, 21].

In response to all these demands to develop cheap, thin, integrated smart sensor, a novel thin-film sensor for the multi-detection of humidity, temperature and flaws was developed. The sensor is capable of detecting several physical parameters without incurring cross-talk and protect the structure from the presence of ice as well as remove the eventual presence of ice on the structure. The sensor reported is simple resonant circuit sensor, which consists of square spiral inductor, characterized by a single conductive trace (copper) on a dielectric substrate, with the turn's spiral all the way to the centre of the coil. In our previous work we presented the Spiral Passive Electromagnetic Sensor (SPES) device [22] as sensor for NDE/SHM for composite samples. In the work reported here we are investigating the capability of the sensor to detect damage and give information on the dimension of the flaws. Moreover we have exploited the capability of the SPES system to monitor variation in temperature and humidity. SPES present a solution to address the need of a multi sensing device able to monitor wireless and without need of battery, environmental parameters as well as defect and crack within the structures. The device could also be used to work as anti-icing/de-icing device if wired to a power supply.

The key advantage of this work is given by its intrinsic multi-functionality given by its internal structure. Indeed, the use of polyimide allows to monitor humidity and temperature without the use of complex pattern [23-26] or additional coating [27, 28] that can affect the mechanical properties of the sensor and increase the manufacturing cost. Another important feature is its robustness. Because the sensor is just a spiral open trace as reported by Woodard [28], even damaged could still be functional: if the conductive trace is interrupted by any damage, the sensor will act as spiral resonant sensor with a shorter length and with a new resonant frequency. This characteristic is particular useful for damage detection.

2. DEVICE FABRICATION

The SPES sensor used is a square spirals resonant circuit, characterized by a single conductive trace (copper) on a dielectric substrate (polyimide or FR4), with the turn's spiral all the way to the centre of the coil as reported in the Figure 1. The outer diameter (l) of the square, eighteen turns spiral inductor, was ~100 mm. The width (w) of each trace was 2mm and the spacing between the adjacent electrodes (g) was 0.2mm.

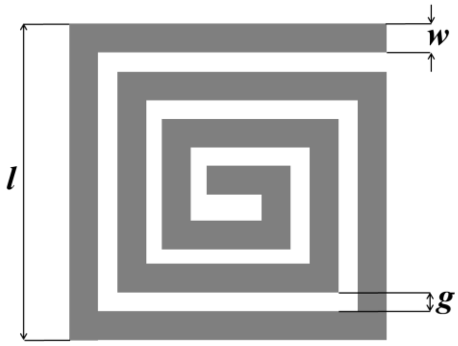


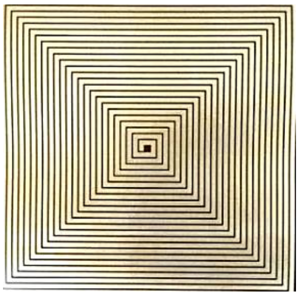
Figure 1 Example of geometry of the SPES device

The thickness of the sensor is related to the manufacturing process adopted and the material used as substrate. Two sensors were manufactured using copper as conductive trace and for the substrate, polyimide and FR4 respectively. The first type of sensor was manufactured using etching technique. In particular 1 oz of copper on one side, and applying silver finish on the trace in order to protect the copper trace. The etched SPES present a total thickness of 110 um. The electrical properties of the sensor are reported in Table 1:

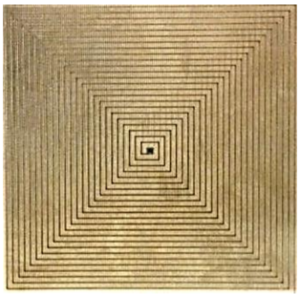
Table 1 Electrical properties for the SPES system on polyimide substrate.

Dielectric Strength	4.2 KV/mil
Dielectric Constant	3.5
Dissipation Factor	0.02
Surface Resistivity	10^{11} ohm/sq
Volume Resistivity	10^{11} ohm-m

The second sensor was made using a milling process, having FR4 as substrate, with a total thickness of 2 mm. The resonances of the sensors are ~37 MHz for the sensor realized on polyimide and ~32 MHz for the one fabricated on FR4 (The resonant frequencies are determined wiring the sensors directly to the spectrum vector analyser). The sensor on the polyimide substrate, due to its slenderness and the easiness to bend itself, is fixed on a polyethylene layer, 1mm thin, ensuring a better and uniform coupling with the antenna. Moreover the added substrates, acting as a dielectric, explain the highest resonant frequency respect to the sensor on the FR4.



Copper trace on polyimide layer



Copper trace on FR4 substrate

Figure 2 Spiral Passive Electromagnetic Sensors

2.1. Sensor Description

The SPES sensor was excited with an external loop antenna having shape and dimension similar to the sensor. The sensor can modelled as an inductor-capacitor (LC) tank circuit, where the copper coil forms both the inductor and the capacitor. The sensor does not present any electronic circuit, but rather an inherent capacitance due to the geometric design and the inductance represented by the spiral metal trace. When exposed to an external radiofrequency (RF) field, the sensor resonates. The sensor is powered and interrogated by magnetic field, using the return loss parameter as measured by a network analyser. This makes the sensor work wirelessly and passively. Figure 3 shows the probe connected to a spectrum analyser (AGILENT N9913A 4 GHz FieldFox Handheld RF Combination Analyzer).

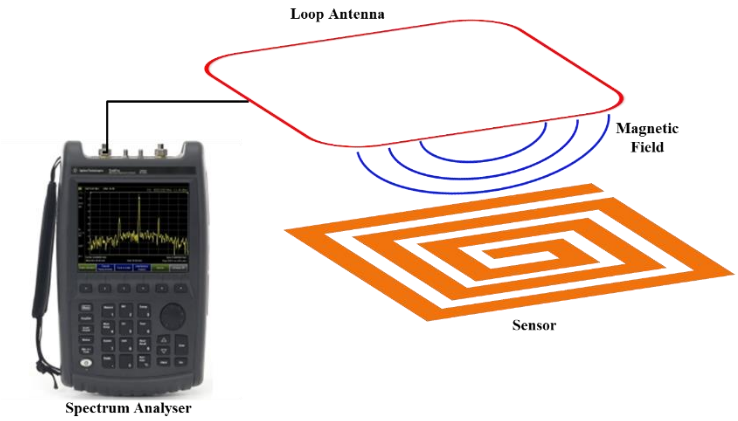


Figure 3 Loop antenna connected to a RF Network Analyzer powering and interrogating a SPES sensor

When excited by a changing magnetic field through a conducting loop or coil, electromagnetic induction (described by the Faraday's law) generates a current through the coil. Each turn of the metal spiral has a different voltage, so any turn's segment creates a potential difference between close parallel trace and thus an electric field. The blue arcing lines in Figure 4 illustrate the electric force between parallel traces through the material (this is mirrored overhead the substrate). How deep electromagnetic radiation can penetrate into a material, is a measure of a penetration depth and its strictly related to the permeability properties of the material and to the design and the dimension of the sensor.

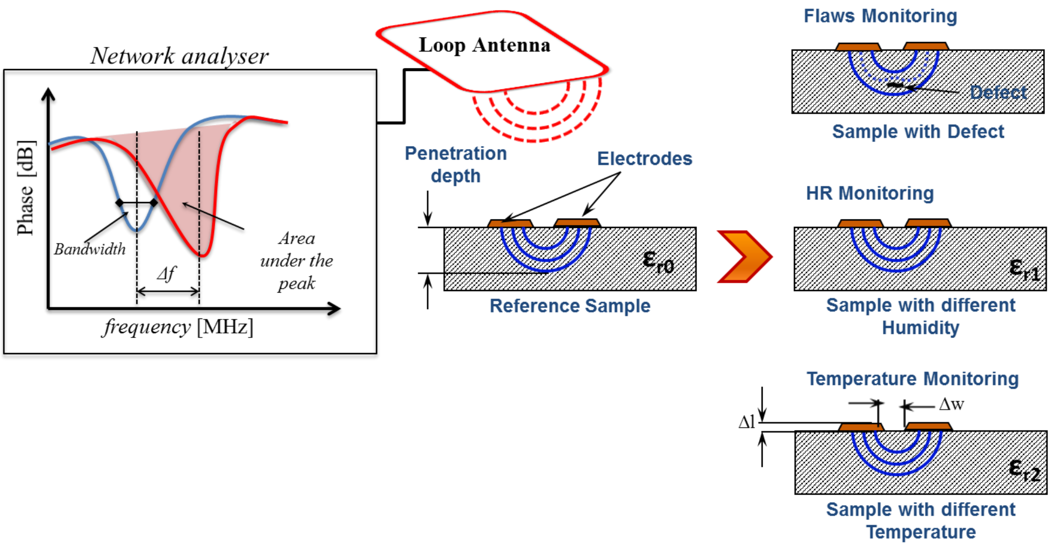


Figure 4 Schematic representation of the sensing mechanism of the SPES

Figure 5 shows how the sensor can monitor flaws, temperature and humidity measuring a change in the resonant response. Indeed, any alteration of the sensor's response due to change in temperature, humidity or of the dielectric properties of the materials in the proximity of the sensor can cause a shift the sensor's resonance characteristics of frequency, amplitude, and bandwidth. So, any changes of the signal response of the sensor can be used to detect environmental parameters or presence of damage/flaws within the material in the proximity of the SPES.

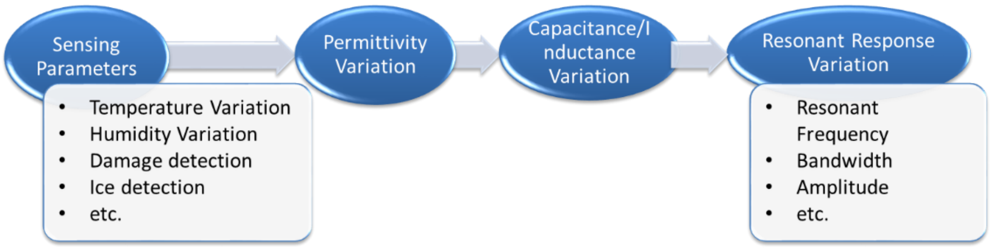


Figure 5 System block diagram of the proposed sensor

The resonant frequency, representing the principal parameter of investigation is related to the interaction of the overall inductance and parasitic capacitance of the sensor as given:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

In particular, the only variable parameters responsible for the shift of the resonant frequency when a change in the structure or in the material properties occurs are the inductance L and the capacitance C. The inductance is strictly related to the design characteristic of the sensor as the turns, the width (*w*) gap (*g*) side (*l*), as illustrated in Figure 1. The capacitance is related to the shape and the geometrical characteristic of the sensor, the permeability of the material used as substrate and the material in the near proximity of the sensor. In a previous work we reported the influence of the sensor design on the capacitance and inductance of the equivalent electrical lumped model and how the electrical nature of the materials on which the sensor is attached/embedded affects the resonant frequency of the sensor. Indeed the presence of flaws cause opposite effect on carbon and glass fibre composites, resulting in increasing the value of the resonant frequency for the conductive samples as the defect increase, instead for non-conductive structures the resonant frequency decrease with the "magnitude" of flaws [22].

2.2. Interrogation method

Based on the capacity of the resonant structures to act as antenna when excited, and then emitting radiation, it is possible to determine the self-resonance frequency, with all related resonating parameters (amplitude, bandwidth, etc.), of the SPES sensor, by using a spectrum analyser with an internal tracking generator, a loop antenna and a directional coupler (is internal in the field fox analyse), as reported by S. Roleson [29]. A swept input frequency was sent by the tracking generator to the loop probe. The loop antenna connected through the directional coupler, reflects most of the incident energy it receives, which is send directly in to the spectrum analyser. This configuration can act as an absorption wave meter. Indeed when the SPES device, with a natural resonant frequency within the swept-frequency range, is in the proximity of the antenna its resonant frequency can be visualized as a dip in the spectrum trace. The curve visualised on the analyser is caused by an incident RF absorbed by the structure. So when the resonant frequency is known, a short swept range has to be refined in order to increase the sensitivity of the sensor and allowing the SPES to act as a sensor. Indeed the comparison of the resonant response of the SPES before and after changes in the material properties occur offers the possibility to detect change in temperature and humidity and on the health state of the structure. Any change of these parameters is subtle and can easily be missed or misunderstood, so great accuracy is required, in order to compare the resonant frequency. It must be noted that a change in the instrumentation, surrounding environments could affect the measure leading to false alarm. For the evolving demand for sensor in the aerospace industry, the SPES has been designed to avoid electromagnetic interference with the frequency adopted in the aeronautics. Indeed the sensors' frequencies in the aerospace sector should be less than 74.8 MHz (marker beacon) or greater than 1220 MHz (Distance Measuring Equipment (DME)). The operation range for both SPES devices used in this work is within 10 – 60 MHz.

3. SMART SENSING

Measurements are related to changes in the sensor's resonant response such as dielectric or permeability changes to material in the sensor's electromagnetic field. The distributed electric field of the SPES penetrates through the dielectric layer so that the capacitance and consequently the resonant response of the sensor is modulated by a change in temperature or humidity or by the presence of defects.

Each experiment was performed ensuring that the sensor was in the same orientation and distance with respect to the antenna and with the same gap between the sensor and the sample tested. Indeed, the resonant response is dependent not only on the dielectric constant of the material substrate (FR4 or polyimide), but also on the coupling between the SPES and the substrate on which it is mounted. During the sensing measurement different parameters were controlled such as: resonant frequency, bandwidth, amplitude, quality factor and the area under the peak, in order to understand which one was the most sensitive to the physical state for which the sensor to be measured. The sensor can detect the presence of ice and its metal trace could be heated through an applied voltage. In addition, temperature and humidity monitoring can detect the icing condition, and with a low voltage applied to the SPES it is possible to prevent ice formation (anti-ice system). In order to analyse the smart sensing ability of the SPES four deferent setups were conceived.

3.1. Temperature Sensing

To measure temperature gradients, the electric field of the SPES must penetrate a material whose dielectric changes with temperature. As the temperature of the heater increase, the sensor varies the dimensions of the conductor lines and the dielectric of the polyimide substrate change, changing the sensor capacitance and inductance, and thereby affecting the resonant response. Variations in temperature affect mainly the resonant frequency and the area under the phase –frequency curve of the sensor. The distributed electric field of the conductive trace of the SPES penetrates through the polyimide layer so that the capacitance and consequently the resonant response of the sensor are modulated by temperature.

The characterization of the wireless passive temperature sensor was tested attaching the sensor on a silicone blanket heater connected to ACR 3 Hot Bonder (BriskHeat®). The temperature was changed from 21℃ to 60 ℃ and monitored using a thermocouple attached on centre of the topside of the SPES. The resonant response parameters have been collected after two minutes the thermocouples registered the desired temperature. The deviation of the temperature during measurement was ±0.5℃. During the measurement the humidity in the room was 42% HR with a deviation of ±1%HR. The SPES device was activated wirelessly using a loop antenna of 100 mm diameter connected to the spectrum analyser placed at 100 mm of distance from the device. The setup is illustrated in the figure below.

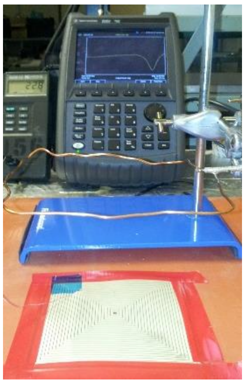
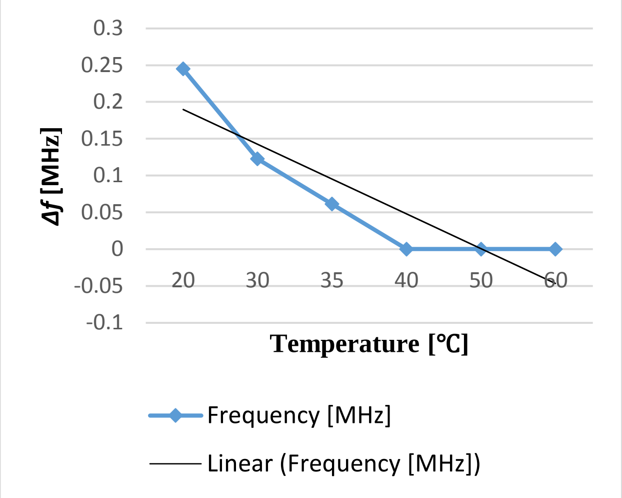
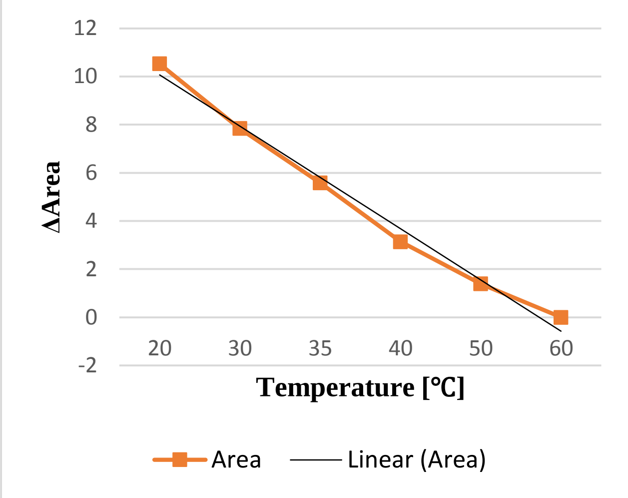


Figure 6 Temperature Sensing Setup

Error! Reference source not found.Error! Reference source not found. shows the sensor temperature response from 20 to 60 °C for both parameters. The results show that the area under the curve is more sensitive to temperature variation respect to the resonant frequency. In particular the SPES provides a sensitivity of 12.25 kHz/℃ from 21℃ to 40 ℃, using the resonant frequency as a sensitive parameter. Between 40 and 60 degree the temperature variation does not affect the resonant frequency. Highest sensitivity of 269.98 kHz*dB/℃ is reported when the area under the curve is used as sensing parameter. Moreover, as reported in **Error! Reference source not found.**b**Error! Reference source not found.** the graph shows a linear trend as the temperature increase.



a) Plot showing the temperature vs. shift in resonant frequency



b) Plot showing the temperature vs. area under the peak

Figure 7 Temperature Sensitivity of the SPES

3.2. Humidity Sensing

Humidity monitoring is strictly related to the material used as substrate. Indeed humidity variation does not affect the inductance of the sensor. In order to monitor humidity variation, as for the temperature sensing, the electric field of the SPES must penetrates a material whose dielectric is affected by humidity variations. As reported by Melcher et al. the polyimide absorb water content change its dielectric properties [30]. Indeed, the SPES device manufactured on a polyimide substrate show the ability to monitor humidity variation. The device makes use of the coil interwinding capacitance (C_{int}) and substrate distributed capacitance (C_{dis}) as shown in the Figure 8. Moisture absorbed by the polyimide substrate causes a hydrolysis effect, which breaks the polyimide's internal carbon–nitrogen bonds. This alters the internal electrical polarization[31], which affects the permittivity of the polyimide. Therefore altering the distributed capacitance cause a shift in the resonant frequency.

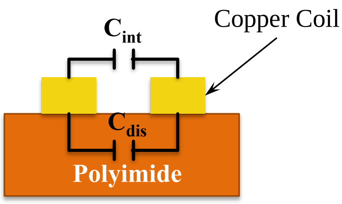
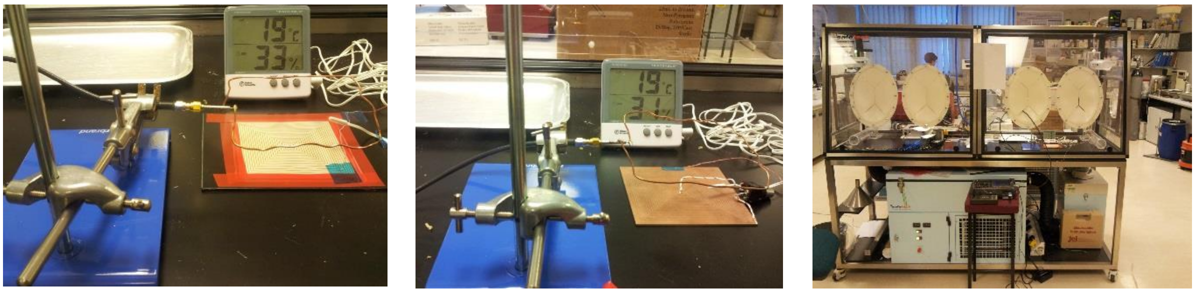


Figure 8 capacitance

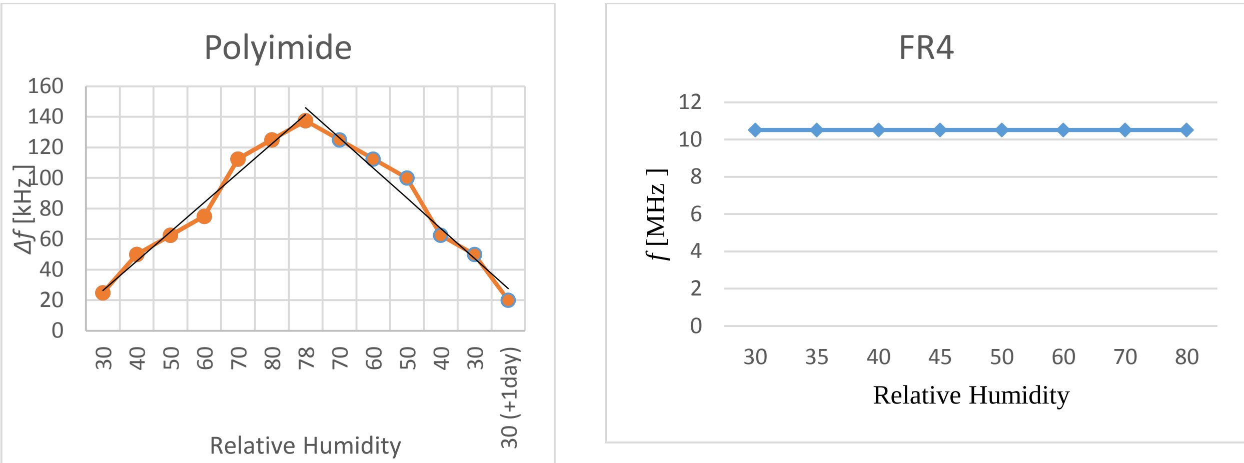
The characterisation of the humidity responses were carried out placing the SPES within a Climate-Zone system (CTS Europe, Portsmouth, UK) with the air temperature kept constant at 19.0 ±0.5℃. The humidity is increased from 30% to 80% RH then decreased back to 30% RH in almost 10% RH increments and measurements are taken waiting two minutes once the chamber has reached the request humidity. The SPES device was activated wirelessly using a loop antenna of 100 mm diameter connected to the spectrum analyser placed at 55 mm of distance from the device. The setups are illustrated in the figures below.



a) SPES on polyimide layer b) SPES on FR4 substrate c) Humidity Chamber

Figure 9 Humidity Sensing Setup

Error! Reference source not found. presents the measured resonant frequency shift as a function of humidity range from 30 to 80 %H.R. **Error! Reference source not found.**b shows the effect of humidity on the resonant frequency for the sensor on FR4 substrate. This proves that humidity variations are detected only by the permittivity change of the material under the coil. De facto, as illustrated in **Error! Reference source not found.**a, a shift of the resonant frequency in response to humidity variation occur when polyimide is used as substrate for the metal coil. As humidity increases, the overall dielectric constant of the polyimide increase and the resonant frequency of the sensor shift to higher frequencies. In the whole test humidity range, resonant frequency changed about 112.5 kHz, which means the sensitivity of the SPES is about 2.3 kHz /%H.R. The response of the sensor is repeatable, with a frequency shift of 112.5 kHz between low and high humidity levels.



a) Plot showing the relative humidity vs. shift in resonant frequency using the sensor on polyimide substrate

b) Plot showing the relative humidity vs. shift in resonant frequency using the sensor on FR4 substrate

Figure 10 Humidity sensitivity of the SPES

Moreover Figure 10 illustrates how the humidity absorption time required by the polyimide layer is higher than the acquisition time used for the test (2 min). Indeed, due to the time required by the sensor to reach a specific value of HR%, the data point at 78% is higher than the one at 80%, as the full sorption of water vapour within the substrate was not completed. The same behaviour was observed when the sensor was placed at 30% HR and the data were collected 24 hours later. The value of relative humidity the day after was similar to the value collected at the beginning of the experiment.

3.3. Damage detection

The capability of the sensor to monitor damage was proved on laminated samples. In particular, composite structures can suffer of barely visible impact damage (BVID) [32, 33] caused by low-velocity impacts (energy level of 10–30 J) such as tool drops, bird strikes and hailstones[34, 35] that can cause a loss in structural integrity and it is a big challenge to detect the associated delamination or cracks. In order to determine the presence of damage inside the samples, and to ensure the repeatability of the experiments, the following experimental procedure was followed. Eight samples were manufactured in a single batch using VARTM (Vacuum assisted resin transfer moulding) process. Seven 'Triax' fabric (+45°/90°/-45°) of 600gsm and one plain weave dry carbon fabric by Sigmatex were infused using an epoxy resin by Sika. The plate obtained from the infusion was cut using a diamond-coated disk on a table saw with guides, obtaining eight coupons. The resulting coupons were 150mm x 100mm with a thickness of 5.50 mm (with a standard deviation of 0.32 mm). After ensuring that all samples present the same resonant frequency, the coupons had to be damaged by means of a controlled manner. For this reason a low-velocity drop weight impact rig was used to induce damage to the laminates. Five different impacts were performed at different energy: 10, 20, 25, 30, 35 Joule respectively, leaving three intact samples as reference.

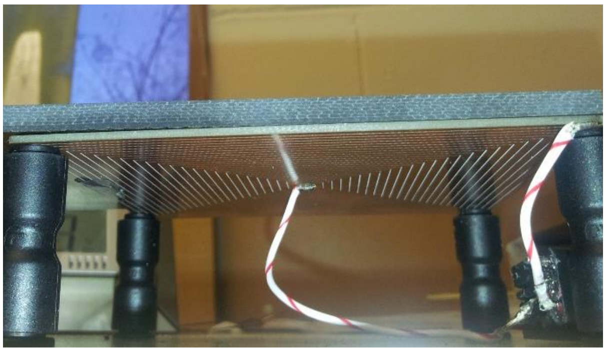


Figure 11 Interrogation Setup

The sensor was placed on the non-damaged side of the samples and the resonant frequency was reported and compared with the undamaged samples. The same sensor was used for all the samples, and in order to ensure a good adhesion to the sample and a repeatable measure, the SPES device on polyimide was substitute with the SPES device on FR4 substrate wired to the spectrum analyser (as illustrate in **Error! Reference source not found.**). To avoid interference the SPES was placed at 4 cm from the ground. Figure 12 reports the resonant frequency for the different impacted samples, where the reference is the undamaged sample and the sensor represent the resonant frequency of the SPES in free air.

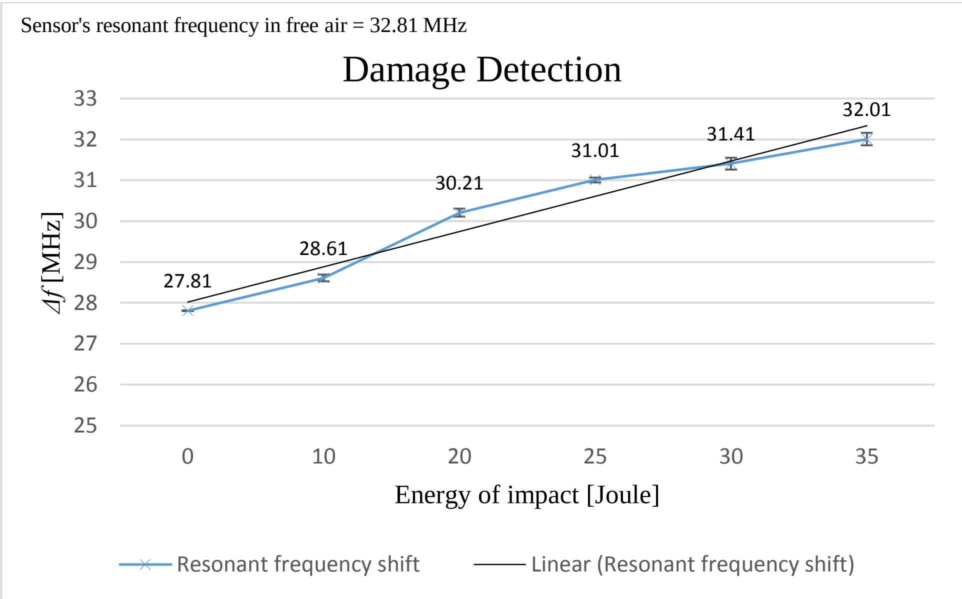
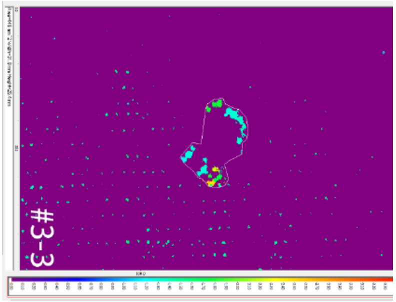


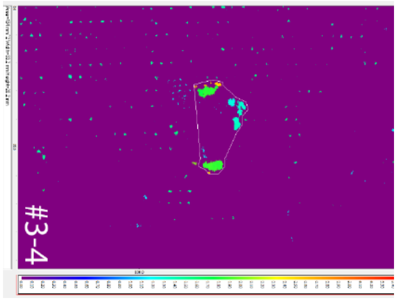
Figure 12 Comparison of resonant frequency for CFRP samples tested with different impact energy.

In the whole test, resonant frequency changed about 4.20 MHz, between the damaged (35J) and the undamaged one, which means the sensitivity of the SPES is almost ~0.1 MHz /Joule. The response of the sensor is repeatable, with a frequency shift of maximum ~0.03 MHz, and a standard deviation of ~0.3 MHz. The impacted samples were also investigated using the ultrasonic C-scan to have a comparative NDT technique (Figure 13a).

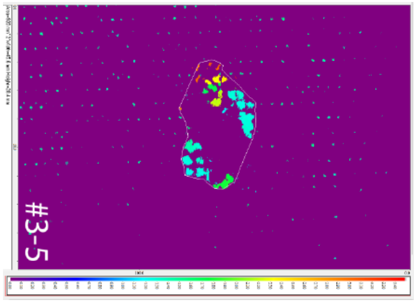
a) Sample Impacted at 10 Joule



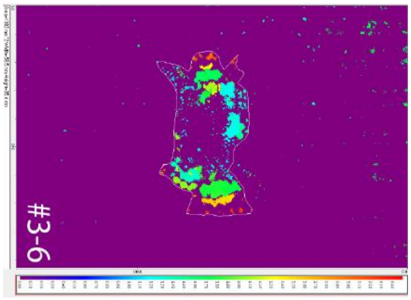
b) Sample Impacted at 20 Joule



c) Sample Impacted at 25 Joule



d) Sample Impacted at 30 Joule



e) Sample Impacted at 35 Joule

Figure 13 Ultrasonic C-scan from the top surface (non damaged side): a) sample impacted with 10 J; b) sample impacted with 20J; c) sample impacted with 25 J; d) sample impacted with 30J; e) sample impacted with 35J.

4. DE-ICING AND ANTI-ICING FUNCTION

Due to its intrinsic nature, SPES device have shown interesting properties that can be exploited for both de-icing and anti-icing applications. The SPES device can detect icing condition, in particular, the presence of an ice layer can be detected with a shift of the resonant frequency due to change in the permittivity of the layer over the sensor, based on the higher dielectric constant of ice among the air [36]. Moreover, the SPES surface mounted or embedded within the composite structure can be used to rapidly increase the temperature of specific parts of the structure. Thus, the SPES device can be activated only in the critical parts of the aircraft to prevent icing conditions or where ice has been detected.

Figure 14 shows the setup for test the anti-icing/de-icing properties. The SPES device on polyimide layer was wired with crocodile pins at both ends of the conductive trace to a power supply.

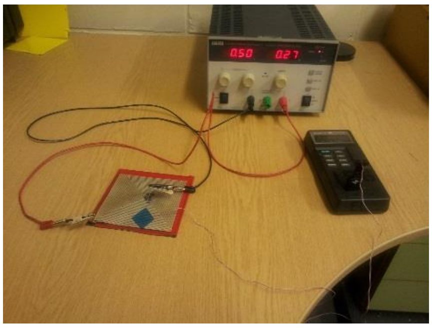


Figure 14 Anti-icing/De-icing setup

The test was conducted applying increasing values of voltages to the sensor. The graph in Figure 15 represents the evolution in time of the temperature recorded by the thermocouple attached on the copper trace of the SPES. The temperature measures were monitored a three different times: at the beginning of the test (t=0 min), after one minute (t=1 min), and after two minutes (t=2 min). The temperature was raised from room temperature up to almost 100°C with a maximum voltage of 5.25 Volt.

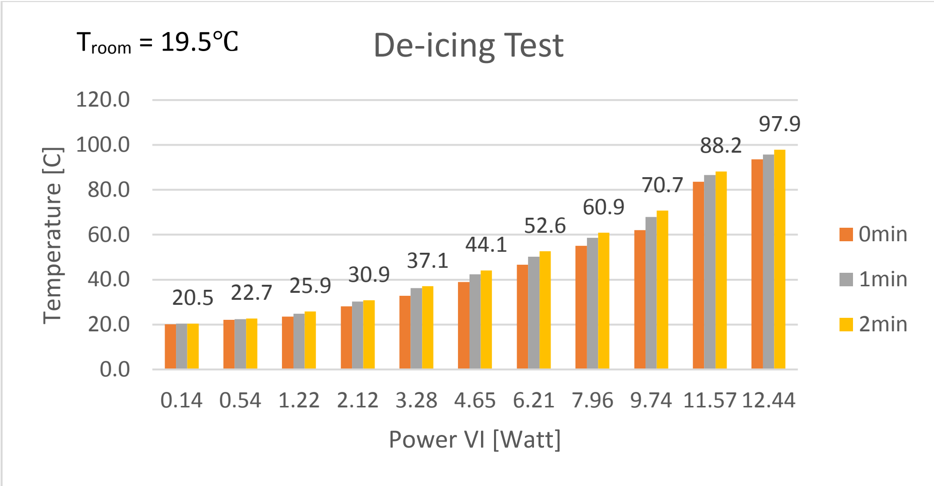


Figure 15 De-icing Test 1

In conclusion, results from the tests clearly show that SPES device are very promising for both anti-icing and de-icing applications. Ice formation usually occurs when the static air temperature (SAT) is between -20 and +2°C, therefore a maximum increase in temperature of about ~25°C is enough to melt the ice on the top surface of a structural component.

Test performed at room temperature have shown that a temperature increase of 25°C can be achieved when 3V are applied to the SPES, with a power consumption of ~5W (de-icing). Instead, icing condition can be avoided using a power as low as ~0.5W (anti-icing). Since SPES temperature increase can show non-linear behavior towards ambient temperature further measurements at ambient temperature as low as -20C need to be performed to confirm the data. It is important to underline that the SPES device can achieve higher value of temperature adjusting the time window of the current excitation (see Figure 16). In this manner, the system can be optimized according to the external environmental conditions.

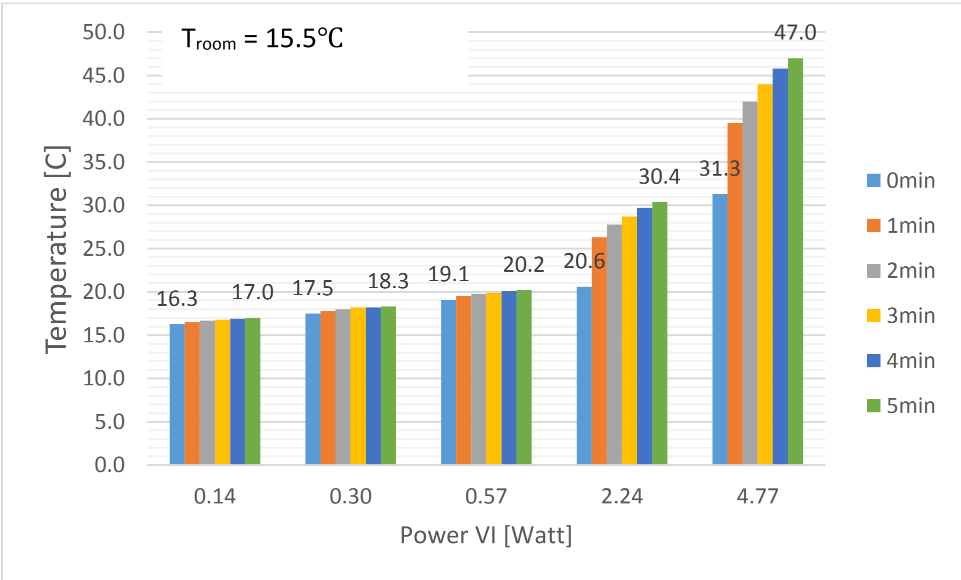


Figure 16 De-icing Test 2

5. SENSOR PERFORMANCE

The signal amplitude of the sensor decreased as the separation distance between the sensor and detection antenna increased. An experiment was conducted to measure the variations of the sensor's amplitude due to the increasing separation distance from the antenna (using a wireless setup). Results showed that if the sensor was aligned with the antenna, the maximum separation distance between the sensor and the antenna was ~200 mm for the SPES with the polyimide substrate and ~150mm for the FR4 one. Figure 17 show the interrogation distance versus the amplitude of the signal. The separation distance can be further improved by increasing the power at the detection coil, or use a multi-turn detection coil. Indeed, the distance is significantly affected by the coil configurations of the antenna and the sensor, which are directly related to the system energy transmission efficiency.

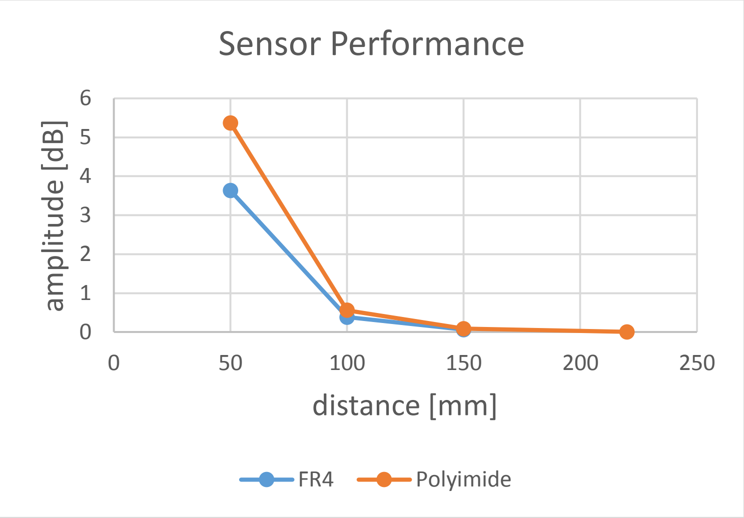


Figure 17 Sensor Performance vs Interrogation distance for both SPES devices

6. CONCLUSIONS

The design and fabrication of a wireless, passive smart monitoring sensor for potential use in aerospace applications is presented. This simple and cost-effective sensor is based on a resonant circuit, with a spiral metal trace on a dielectric substrate. This configuration allows the sensor to detect environmental parameters (temperature and humidity) and presence of flaws (cracks and delamination) by measuring the changes in the resonant response (e.g.: sensor's resonant frequency). Environmental parameters were monitored using polyimide as substrate. The sensor showed a lower resonant frequency at a lower percentage of relative humidity, and vice versa. An inverse trend has been shown for temperature sensing, with lower resonant frequency at higher temperature, and vice versa. Data obtained from the tests exhibited a linear relationship between the area under the curve of the resonant response and temperature variation. Compared to an undamaged sample, a shift in the resonant frequencies occurred when the sensors were placed on a damaged composite panel, thus revealing the structural defects.

The great advantage of the sensing system presented in this work is the ability to monitor different parameters using the same device. The sensor offers also the capability to work either wireless interrogated by a loop antenna or wired connected to a device able to detect its resonant response. Moreover, the electro thermal coupling effect of the copper trace was investigated in order to exploit the smart function of the SPES. The device is able to detect the presence of ice as well as icing condition, and act as an ice protection system (de-icing/anti-icing). Indeed, the electrical resistance variation and the internal Joule heating source provided by the metal trace give the possibility to reach ~50℃ with a power of ~5W, or up to 20℃ with just ~0.5W. All these characteristics make the SPES a competitive choice in structural health and environmental monitoring for use in aerospace sector.

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